University of Tuzla,
Faculty for Mechanical Engineering, Postgraduate study
Modelling, Simulation, Optimisation

Design Integration for Screw Compressors

Part 1:
Methods and Tools in Screw Compressor Design

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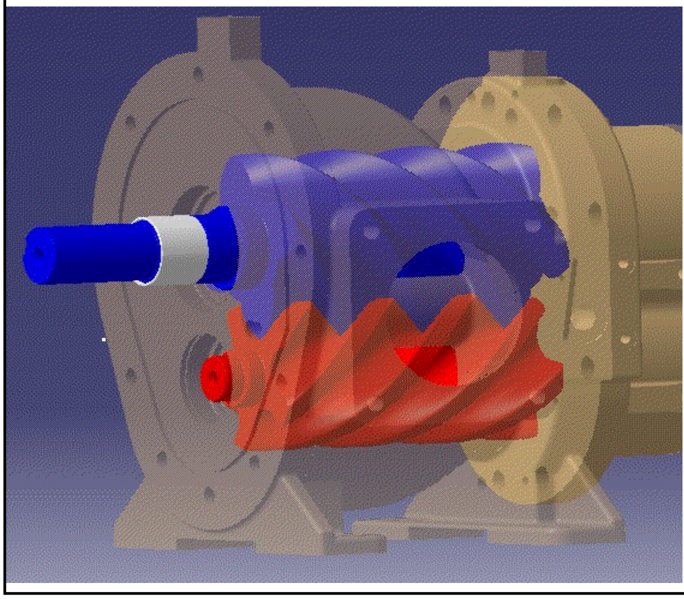
Positive displacement rotary machine



Brief history:

The operating principle known for more than 100 years

1942 *Lysholm* of SRM – patent on working principle and profile.

1952 *Nilsen* - patent on circular profile, SRM designed first commercial screw compressor.

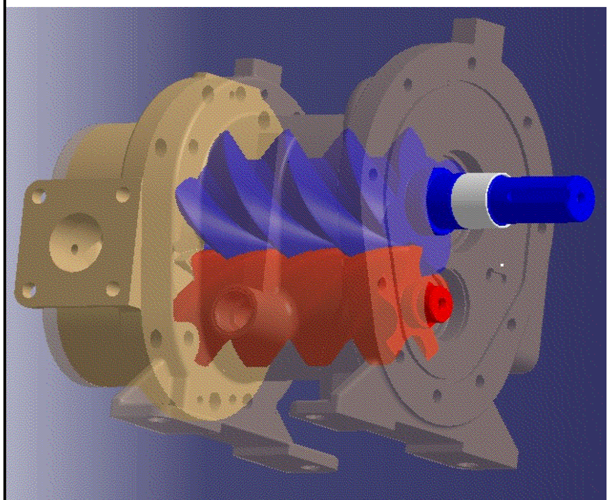
Until 1990's SRM was practically the only licensor of screw compressor technology

1985 Independent development of screw compressors begins with rack generated profiles from Rinder, Stosic and some Japanese companies.

1995 Significant increase in number of screw compressor manufacturers.

2005 Screw compressor industry needs tool for concurrent engineering of screw compressors.

Screw compressor applications



Dry & oil injected:
- Air compression
- Refrigeration
- Process fluids

(35) 50 – 800 mm dia
0.3 – 800 m³/min

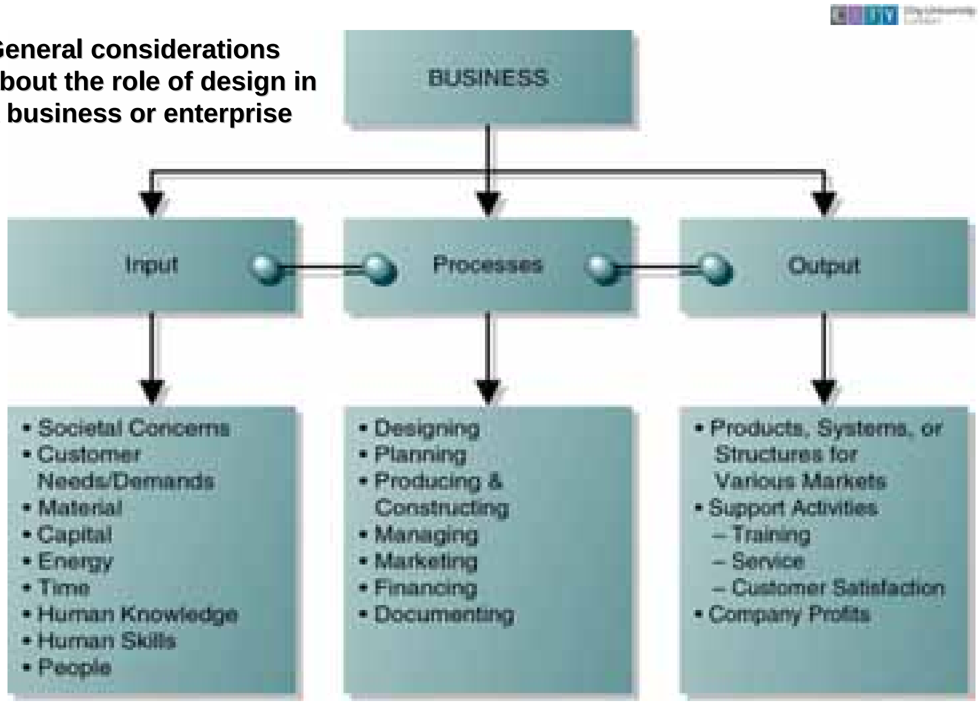
High Volumetric efficiency

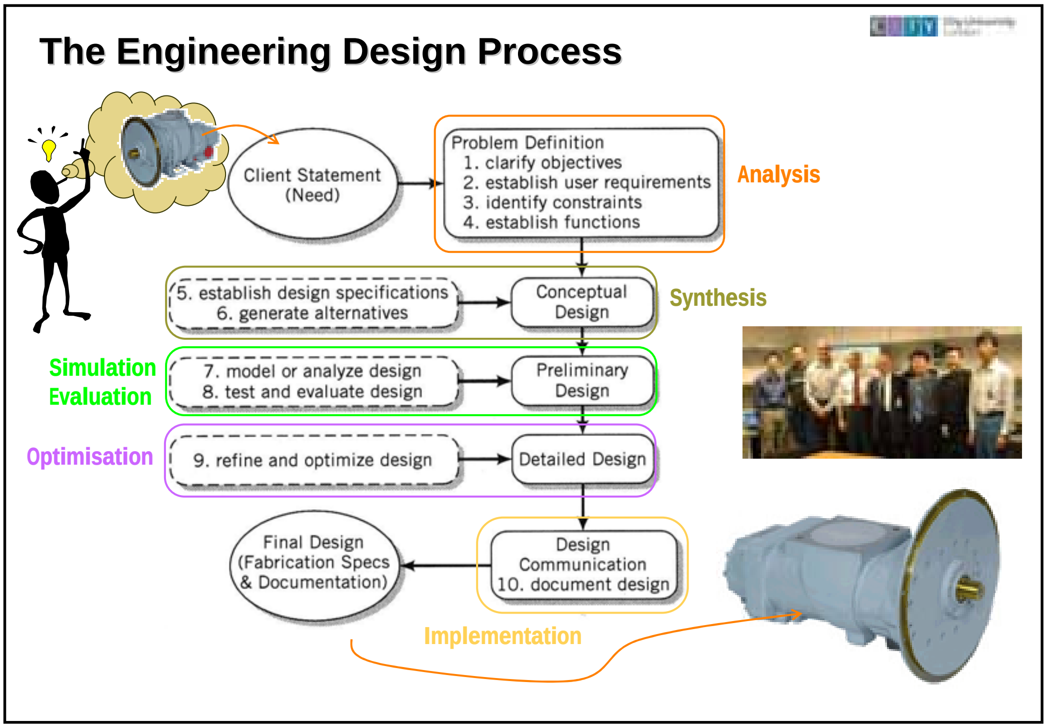
80% of industrial compressors produced are screw compressors

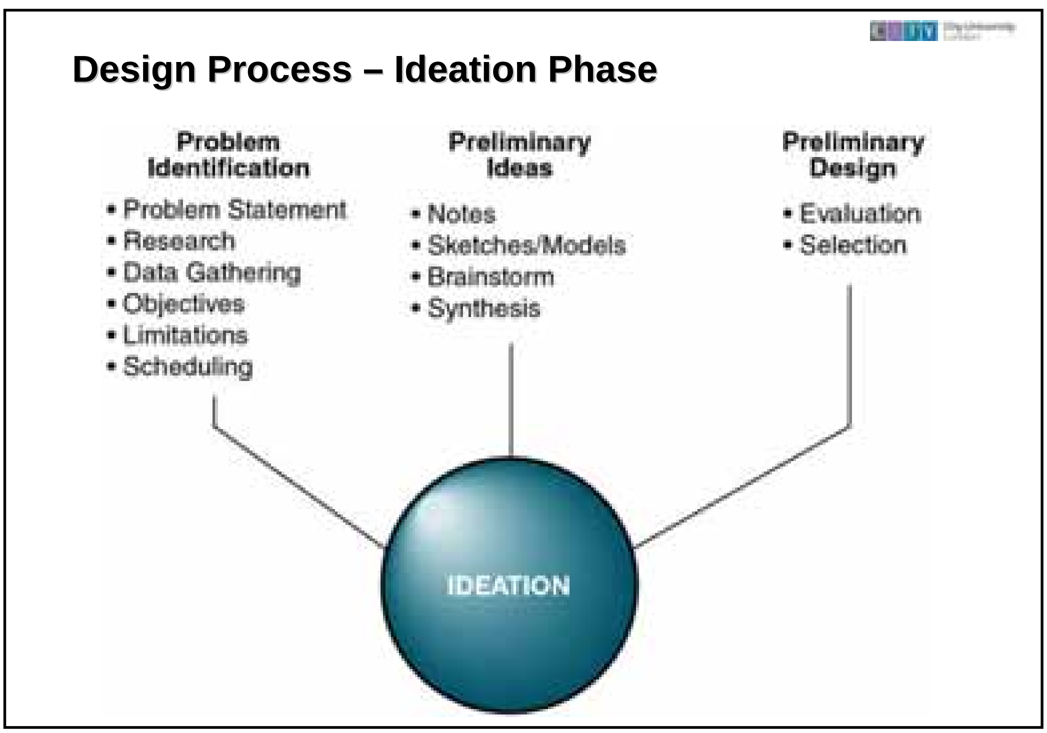
17% energy produced in developed countries used for compression

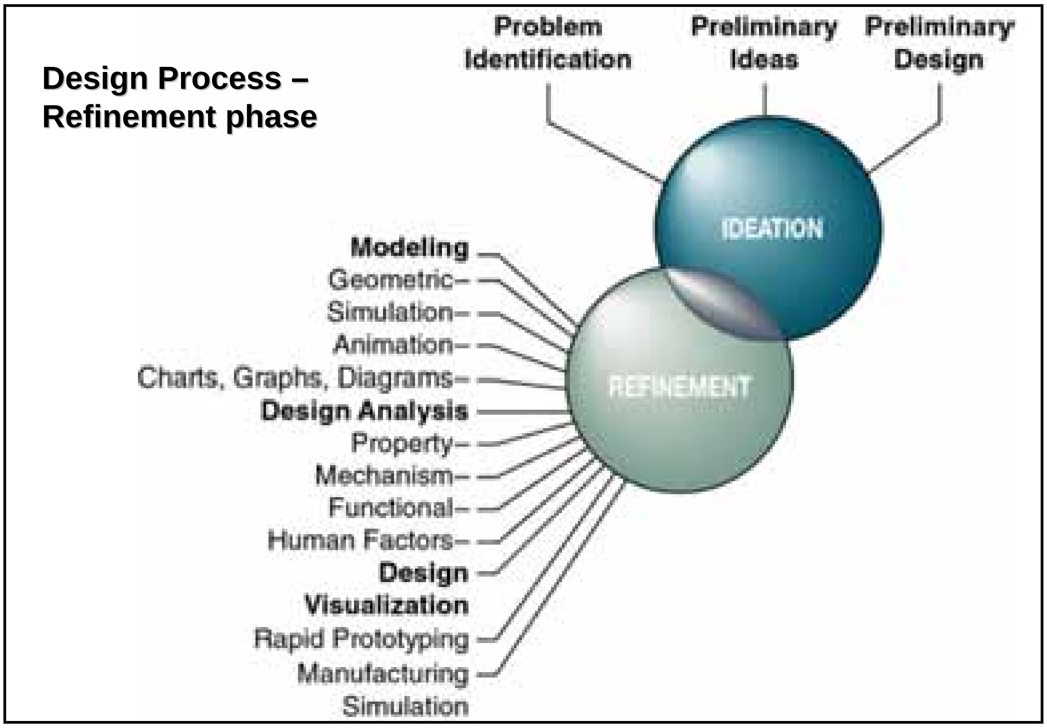
25% energy in USA during summer is used for refrigeration and air-conditioning

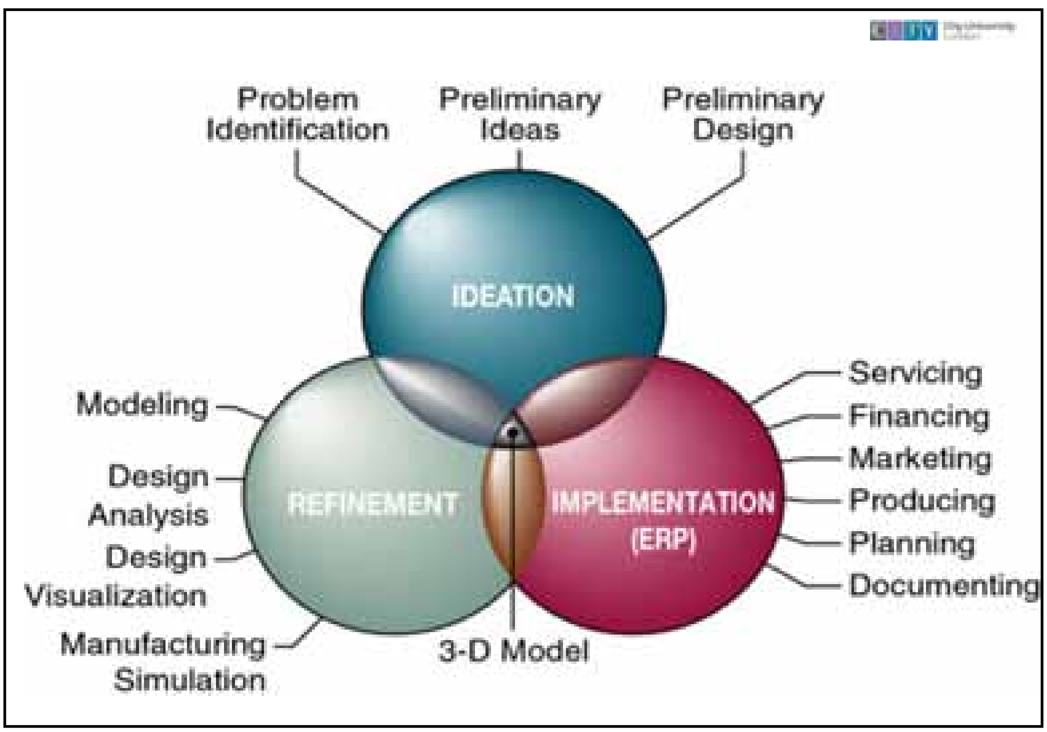
General considerations about the role of design in a business or enterprise




The Engineering Design Process
Client Statement
(Need)
Problem Definition
1. clarify objectives
2. establish user requirements
3. identify constraints
4. establish functions
Analysis
5. establish design specifications
6. generate alternatives
Conceptual Design
Synthesis
Simulation
Evaluation
7. model or analyze design
8. test and evaluate design
Preliminary Design
Optimisation
9. refine and optimize design
Detailed Design
Final Design
(Fabrication Specs
& Documentation)
Design
Communication
10. document design
Implementation


Design Process – Ideation Phase
Problem Identification
• Problem Statement
• Research
• Data Gathering
• Objectives
• Limitations
• Scheduling
Preliminary Ideas
• Notes
• Sketches/Models
• Brainstorm
• Synthesis
Preliminary Design
• Evaluation
• Selection
IDEATION


Design Process –
Refinement phase
Problem Identification
Preliminary Ideas
Preliminary Design
IDEATION
REFINEMENT
Modeling
Geometric
Simulation
Animation
Charts, Graphs, Diagrams
Design Analysis
Property
Mechanism
Functional
Human Factors
Design Visualization
Rapid Prototyping
Manufacturing Simulation


Problem Identification
Preliminary Ideas
Preliminary Design
IDEATION
REFINEMENT
IMPLEMENTATION (ERP)
Modeling
Design Analysis
Design Visualization
Manufacturing Simulation
3-D Model
Servicing
Financing
Marketing
Producing
Planning
Documenting

Methods and Tools in Screw compressor design

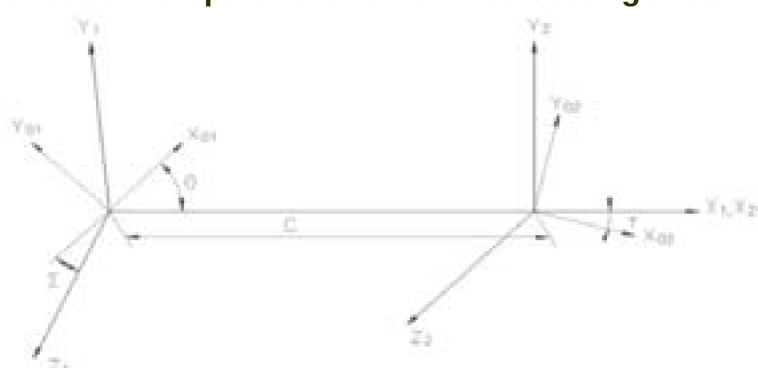
- **2-D design tools -** Conventional approach (60 %)
  - **SCORPATH** (**S**crew **Co**mpressor **R**otor **P**rofiling **and TH**ermodynamics)
  - **2-D CAD Software: AutoCad 2000+**
- **3-D design tools -** More modern approach (35 %)
  - **SCORPATH** (**S**crew **Co**mpressor **R**otor **P**rofiling **and TH**ermodynamics)
  - **3-D CAD** MDT, Inventor, Catia, Solid Works
  - **SCORG** (**S**crew **C**ompressor **R**otor **G**rid)
  - **CFD (CCM)** Comet, Star, CFX, Fluent
- **3-D design management -** Concurrent approach (Only rear users)
  - **-DISCO** (**D**esign **I**ntegration for **S**crew **CO**mpressors)

Basic Screw Compressor Geometry

Rotor lobe profiles must be defined together with the remaining parameters with which the rotor and housing geometry can be fully specified.

- Rotor profile: x and y coordinates, pressure angle
- Helix/lead angle, rotor length
- Interlobe, end and radial clearance
- Suction/discharge ports

General case: non-parallel and non-intersecting axes



Given profile

$$\mathbf{r}_1 = \mathbf{r}_1(t,\theta) = [x_1, y_1, z_1] = [x_{01}\cos\theta - y_{01}\sin\theta, x_{01}\sin\theta + y_{01}\cos\theta, p_1\theta]$$

$$\frac{\partial \mathbf{r}_1}{\partial t} = \left[\frac{\partial x_1}{\partial t}, \frac{\partial y_1}{\partial t}, 0\right] = \left[\frac{\partial x_{01}}{\partial t}\cos\theta - \frac{\partial y_{01}}{\partial t}\sin\theta, \frac{\partial x_{01}}{\partial t}\sin\theta + \frac{\partial y_{01}}{\partial t}\cos\theta, 0\right]$$

$$\frac{\partial \mathbf{r}_1}{\partial \theta} = \left[\frac{\partial x_1}{\partial \theta}, \frac{\partial y_1}{\partial \theta}, 0\right] = [-y_{01}, x_{01}, 0]$$

General case: non-parallel and non-intersecting axes

Meshed profile

$$\mathbf{r}_2 = \mathbf{r}_2(t,\theta,\tau) = [x_2, y_2, z_2] = [x_1 - C, y_1\cos\Sigma - z_1\sin\Sigma, y_1\sin\Sigma + z_1\cos\Sigma] =$$
$$[x_{02}\cos\tau - y_{02}\sin\tau, x_{02}\sin\tau + y_{02}\cos\tau, p_2\tau]$$

$$\frac{\partial \mathbf{r}_2}{\partial \tau} = [-y_2, x_2, p_2] = [x_{02}\sin\tau + y_{02}\cos\tau, x_{02}\cos\tau - y_{02}\sin\tau, p_2] =$$
$$[p_1\theta\sin\Sigma - y_1\cos\Sigma, p_2\sin\Sigma + (x_1 - C)\cos\Sigma, p_2\cos\Sigma - (x_1 - C)\sin\Sigma]$$

Meshing condition (Envelope conjugacy condition)

$$\left(\frac{\partial \mathbf{r}_1}{\partial t}\times\frac{\partial \mathbf{r}_1}{\partial \theta}\right)\cdot\frac{\partial \mathbf{r}_1}{\partial \tau} = -\left(\frac{\partial \mathbf{r}_1}{\partial t}\times\frac{\partial \mathbf{r}_1}{\partial \theta}\right)\cdot\frac{\partial \mathbf{r}_2}{\partial \tau} = 0$$

$$[C - x_1 + (p_1 - p_2)\cot\Sigma]\left(x_1\frac{\partial x_1}{\partial t} + y_1\frac{\partial y_1}{\partial t}\right) + p_1\left[p_1\theta\frac{\partial y_1}{\partial t} + (p_2 - C\cot\Sigma)\frac{\partial x_1}{\partial t}\right] = 0$$

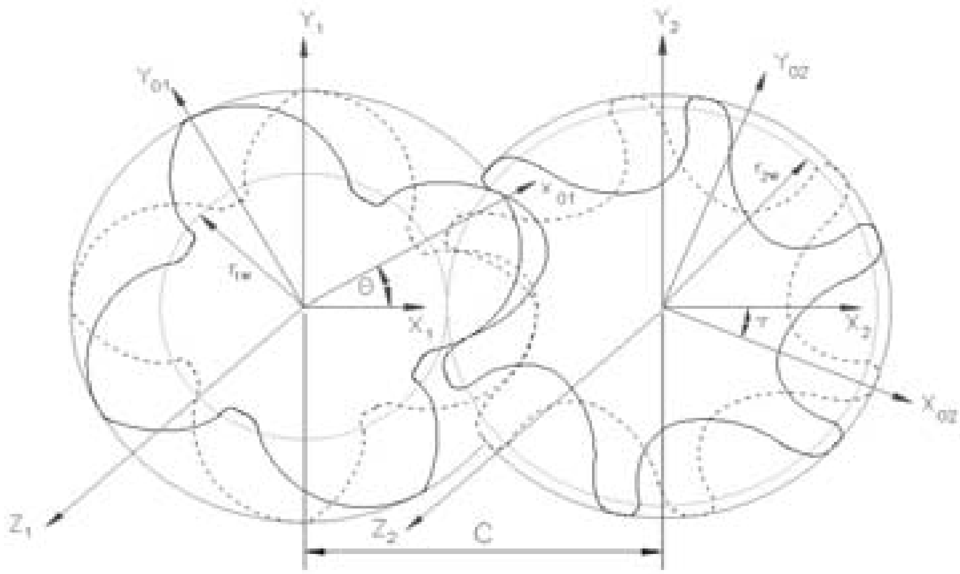
General case:

- non-parallel and non-intersecting axes
  rotor – hobbing tool relation

Special cases:

- p_2=0
  rotor - plate milling tool, grinding tool relation
- Σ=0
  screw compressor rotors

Rotor profile



Given rotor profile

$$\Sigma = 0, \quad i = \frac{p_2}{p_1}, k = 1 - \frac{1}{i}$$

Meshing condition

$$\frac{dy_{01}}{dx_{01}}\left(ky_{01} - \frac{C}{i}\sin\theta\right) + kx_{01} + \frac{C}{i}\cos\theta = 0$$

Meshed profile

$$x_{02} = x_{01}\cos k\theta - y_{01}\sin k\theta - C\cos\frac{\theta}{i}$$

$$y_{02} = x_{01}\sin k\theta + y_{01}\cos k\theta + C\sin\frac{\theta}{i}$$

Rack profile

$$x_{0r} = x_{01}\cos\theta - y_{01}\sin\theta$$

$$y_{0r} = x_{01}\sin\theta + y_{01}\cos\theta - r_1\theta$$

Given rack profile

$$\Sigma = 0, \quad i = \frac{p_r}{p_1} = \infty, \qquad k = 1 - \frac{1}{\infty} = 1$$

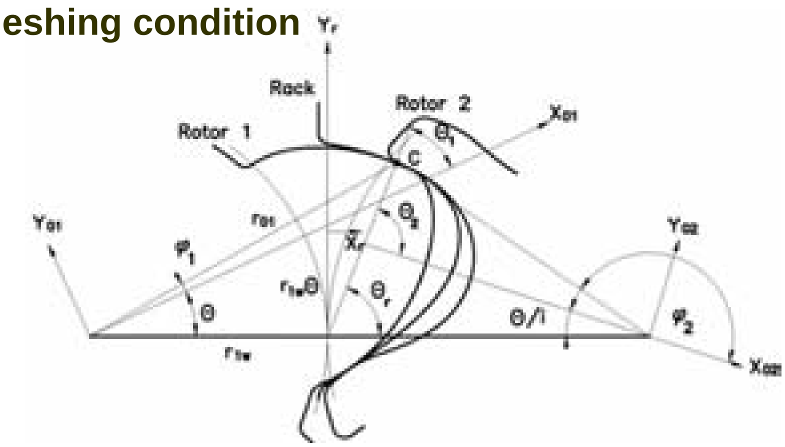
Meshing condition

$$\frac{dy_{0r}}{dx_{0r}}\left(r_{1w}\theta - y_{0r}\right) - \left(r_{1w} - x_{0r}\right) = 0$$

Meshed rotor profile

$$x_{01} = x_{0r}\cos\theta - \left(y_{0r} - r_{1w}\right)\sin\theta$$
$$y_{01} = x_{0r}\sin\theta + \left(y_{0r} - r_{1w}\right)\cos\theta$$

Willis meshing condition

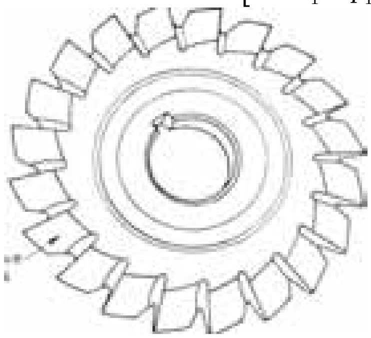


$$\frac{dy_{01}}{dx_{01}}\left(ky_{01} - \frac{C}{i}\sin\theta\right) + kx_{01} + \frac{C}{i}\cos\theta = 0$$

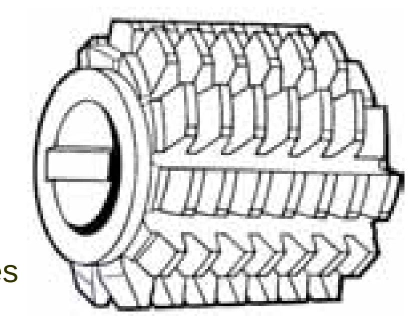
$$\frac{\sin\left(\theta_1 + \theta\right)}{r_{01}} = \frac{\sin\left(\theta_1 - \varphi_1\right)}{r_{1w}}$$

Profile of a plate milling tool/grinding tool

$$[C - x_1 + p_1 \cot\Sigma]\left(x_1 \frac{\partial x_1}{\partial t} + y_1 \frac{\partial y_1}{\partial t}\right) + p_1\left[p_1\theta \frac{\partial y_1}{\partial t} - C\cot\Sigma \frac{\partial x_1}{\partial t}\right] = 0$$



$$\left(R_2 + z_2 \frac{dz_2}{dR_2}\right)\cos\tau + \left(p_1 + C\cot\Sigma\right)\frac{dz_2}{dR_2}\sin\tau + p_1\cot\Sigma - C = 0$$

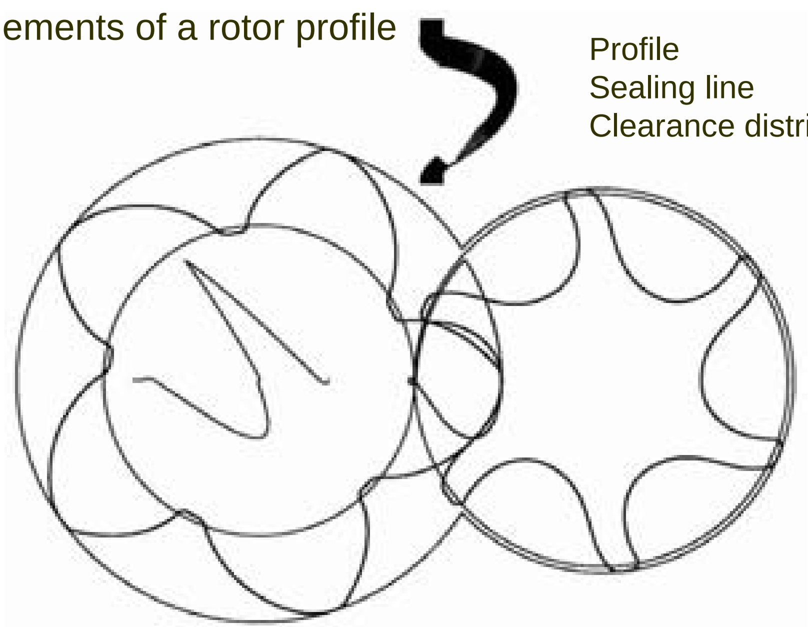


Profile of a hobbing tool

Full meshing conditions for:
Non-parallel and non-intersecting axes

Elements of a rotor profile

Profile
Sealing line
Clearance distribution



Rotor parameters

$$C = r_{1w} + r_w$$

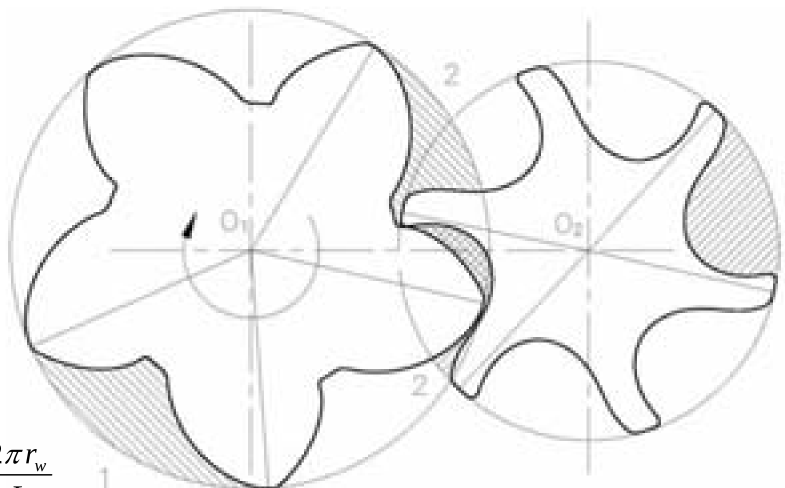
$$i = \frac{r_{2w}}{r_{1w}} = \frac{z_2}{z_1}$$

$$\frac{tg\psi}{tg\psi_w} = \frac{r}{r_w}$$

$$p = \frac{h}{2\pi}$$

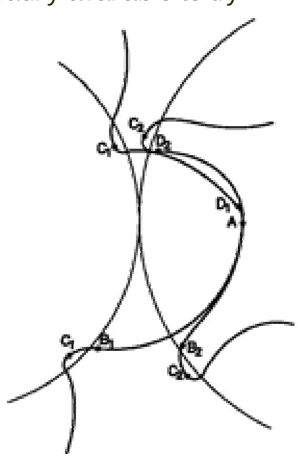
$$\frac{L}{\varphi} = \frac{h}{2\pi} = p$$

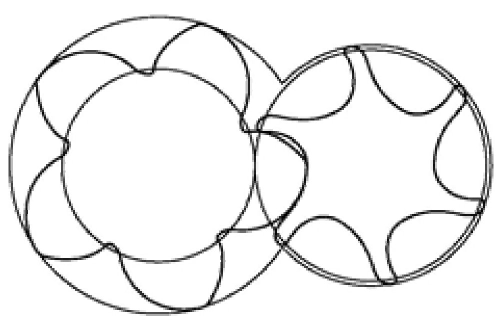
$$tg\psi_w = \frac{\varphi r_w}{h} = \frac{2\pi r_w}{L}$$



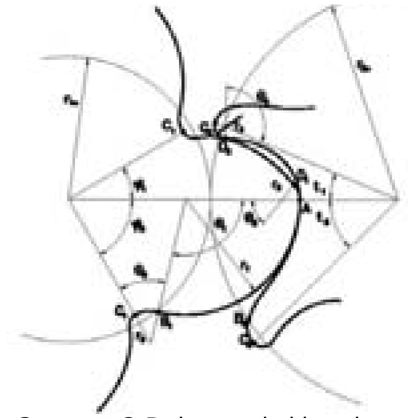
Demonstrator profile

- Rotor generated “N” profile (not patented “N” profile)
- A primary lobe is provided on the male rotor
- Profile consist of series of circles on the main and the gate rotors
- Readily available to try

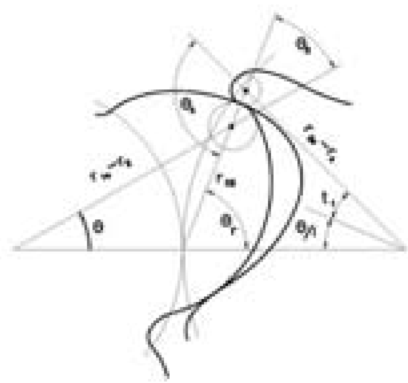




Demonstrator profile



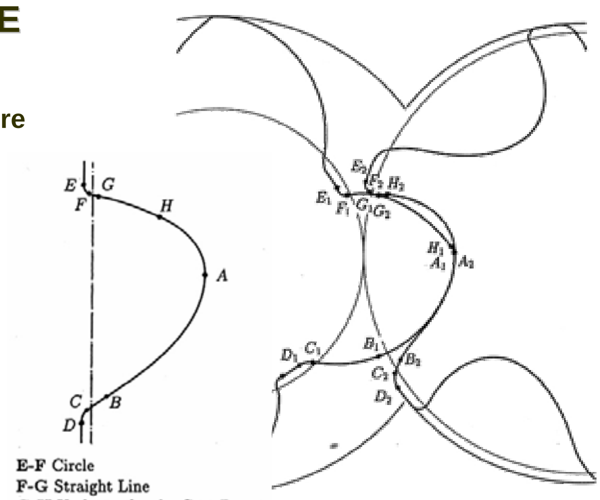
- Segment A_1B_1 is a circle of the radius r_1 on the main rotor
  Angular parameter t varies between $-\theta_1<t<0$
- Segment B_1C_1 is a circle of the radius r_3 on the main rotor,
  Angular parameter t varies between $\pi-\psi_1<t<\pi-\theta_1$



- Segment C_1D_1 is a trochoid on the main rotor generated from the circle of radius r_4 on the gate rotor
  Angular parameter: $-\theta_4-\tau_1<t<-\pi-\tau_1$
- Segment A_1D_1 is a circle of radius r_2 on the main rotor,
  Angular parameter: $0<t<\theta_2$.

'N' ROTOR PROFILE

- **Rack generation procedure**
- **Straight line on the rack (involute rotor contact)**
- **Small torque transmitted**
- **Large displacement**
- **Strong gate rotor**
- **Short sealing line**
- **Clearance distribution**

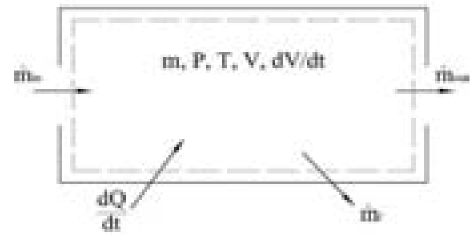


E-F Circle
F-G Straight Line
G-H Undercut by the Gate Rotor
H-A Undercut by the Main Rotor
A-B Arc: p=0.43, q=1
B-C Straight Line
C-D Circle
D-E Straight Line

Thermodynamic calculations

1-D "chamber" model:

- **Differential approach**: conservation of continuity, momentum and energy



- **Working fluid**: Ideal or real
- **Heat transfer** between the fluid and solid compressor parts
- **Liquid injection** modelled
- Model is independent on a compressor geometry

- **Limitations:**
  - Fluid flow is assumed "quasi" one-dimensional
  - Kinetic energy neglected in comparison with internal energy
  - The flow through inlet and outlet chambers assumed to be isentropic
  - The flow through clearances assumed to be adiabatic

Thermodynamic calculations (2)

- **Internal energy**

$$\omega\left(\frac{dU}{d\theta}\right) = \dot{m}_{in} h_{in} - \dot{m}_{out} h_{out} + Q - \omega p \frac{dV}{d\theta}$$

$$\dot{m}_{in} h_{in} = \dot{m}_{suc} h_{suc} + \dot{m}_{l,g} h_{l,g} + \dot{m}_{oil} h_{oil} \qquad \dot{m}_{out} h_{out} = \dot{m}_{dis} h_{dis} + \dot{m}_{l,l} h_{l,l}$$

- **Continuity**

$$\omega \frac{d\dot{m}}{d\theta} = \dot{m}_{in} - \dot{m}_{out}$$

$$\dot{m}_{in} = \dot{m}_{suc} + \dot{m}_{l,g} + \dot{m}_{oil} \qquad \dot{m}_{out} = \dot{m}_{dis} + \dot{m}_{l,l} \qquad \dot{m} = \rho w A$$

- **Leakage flow** $\dot{m}_l = \rho_l w_l A_g = \sqrt{\dfrac{p_2^2 - p_1^2}{a^2\left(\zeta + 2\ln\dfrac{p_2}{p_1}\right)}}$ $\quad w_l dw_l + \dfrac{dp}{\rho} + f\dfrac{w_l^2}{2}\dfrac{dx}{D_g} = 0$

Thermodynamic calculations (3)

- **Liquid injection**

$$\dot{m}_{oil} = \frac{\dot{m}_{oil}}{\dot{m}_{gas}} \dot{m} \frac{z_1}{2\pi} \qquad \frac{dT_o}{d\theta} = \frac{h_o A_o \left(T_{gas} - T_o\right)}{\omega m_o c_{oil}}$$

Nu =2+0.6 Re$^{0.6}$ Pr$^{0.33}$

- **Ideal fluid**

$$U = (mu)_{gas} + (mu)_{oil} = \frac{mRT_{gas}}{\gamma - 1} + (mcT)_{oil} = \frac{pV}{\gamma - 1} + (mcT)_{oil}$$

$$u = f(t), \quad \rho = f(p,t), \quad u \neq f(p) \qquad T = (\gamma - 1)\frac{(1+k)U - (mcT)_{oil}}{(1+k)mR + (mc)_{oil}}$$

- **Real fluid** $u = f(t, p), \quad \rho = f(p,t)$ *Iterative*

- **Wet vapour** $u = (1-x)u_f + xu_g \qquad v = (1-x)v_f + xv_g$

Compressor integral parameters

$$m = m_{in} - m_{out}$$

$$\dot{m} = mz_1 n / 60$$

$$\dot{V} = 60m / \rho_0$$

$$\dot{m}_t = \frac{\left(F_{1n} + F_{2n}\right) L n z_1 \rho}{60}$$

$$\eta_v = \dot{m} / \dot{m}_t$$

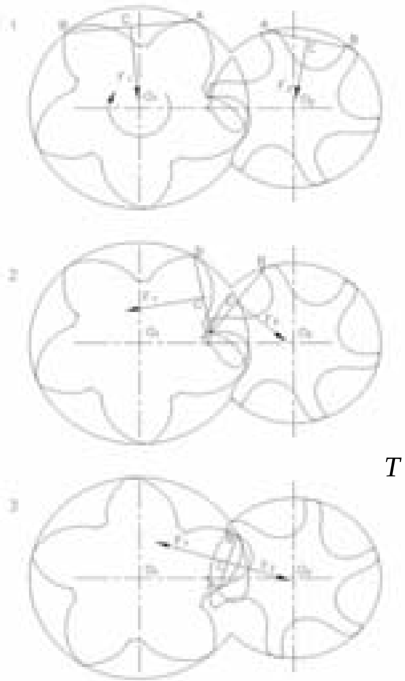
$$W_{ind} = \int_{cycle} V dp \qquad W_{sind} = \int_{cycle} \frac{V}{m} dp$$

$$P_{ind} = \frac{W_{ind} z_1 n}{60} \qquad P_{\sin d} = \frac{P}{\dot{V}}$$

$$W_t = RT_1 \ln \frac{p_2}{p_1}$$

$$W_a = \frac{\gamma}{\gamma - 1} R\left(T_2 - T_1\right)$$

$$\eta_t = \frac{W_t}{W_{ind}} \qquad \eta_a = \frac{W_a}{W_{ind}}$$



Pressure loads

Radial forces

$$R_x = -p\int_A^B dy = -p\left(y_B - y_A\right)$$

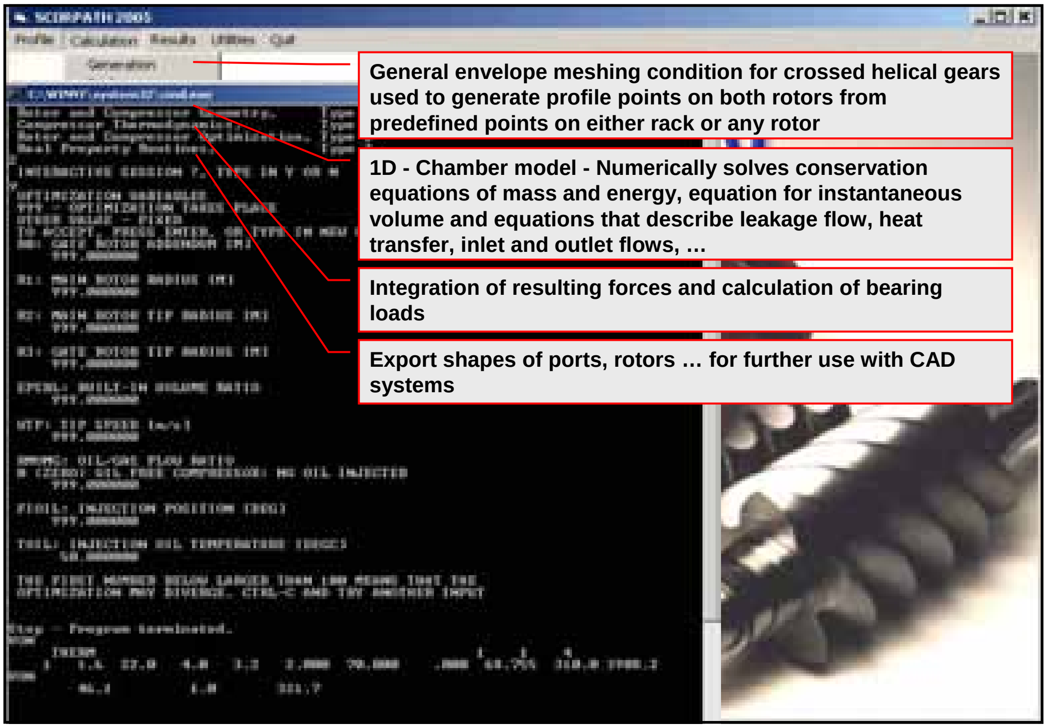
$$R_y = -p\int_A^B dx = -p\left(x_B - x_A\right)$$

Rotor torque

$$T = p\int_A^B x dx + p\int_A^B y dy - 0.5p\left(x_B{}^2 - x_A{}^2 + y_B{}^2 - y_A{}^2\right)$$

Rotor deflections

$$\frac{d^2\delta}{dz^2} = \frac{M}{EI}$$


General envelope meshing condition for crossed helical gears used to generate profile points on both rotors from predefined points on either rack or any rotor
1D - Chamber model - Numerically solves conservation equations of mass and energy, equation for instantaneous volume and equations that describe leakage flow, heat transfer, inlet and outlet flows, …
Integration of resulting forces and calculation of bearing loads
Export shapes of ports, rotors … for further use with CAD systems